ORIGINAL PAPER

Climate change affecting temperature and aridity zones: a case study in Eastern Inner Mongolia, China from 1960–2008

**Jinwei Dong · Jiyuan Liu · Geli Zhang ·
Jeffrey B. Basara · Scott Greene · Xiangming Xiao**

Abstract Recent climate change is substantially affecting the spatial pattern of geographical zones, and the temporal and spatial inconsistency of climatic warming and drying patterns contributes to the complexity of the shifting of temperature and aridity zones. Eastern Inner Mongolia, China, located in the interface region of different biomes and ecogeographic zones, has experienced dramatic drying and warming over the past several decades. In this study, the annual accumulated temperature above 10 °C (AAT10) and the aridity index, two key indicators in geographical regionalization, are used to assess warming and drying processes and track the movements of temperature and aridity zones from 1960 to 2008. The results show a significant warming at the regional level from 1960 to 2008 with an AAT10 increase rate of 7.89 °C·d/year ($p < 0.001$) in Eastern Inner Mongolia, while the drying trend was not significant during this period. Spatial heterogeneity of warming and drying distributions was also evident. Analysis of warming and drying via piecewise regression revealed two separate, specific trends between the first 31 years (1960–1990) and the subsequent 18 years (1991–2008). Generally, mild warming and very slight wetting occurred prior to 1990, while after 1991 both warming and drying were significant and enhanced.

J. Dong (✉) · X. Xiao
Department of Microbiology and Plant Botany, Center for Spatial Analysis, University of Oklahoma, Norman, OK 73019, USA
e-mail: jinwei.dong@ou.edu

J. Dong · J. Liu · G. Zhang
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

J. B. Basara
School of Meteorology, Oklahoma Climatological Survey, University of Oklahoma, Norman, OK 73019, USA

S. Greene
Department of Geography, University of Oklahoma, Norman, OK 73019, USA

Continuous warming drove a northward shift of temperature zones from the 1960s to 2000s, while aridity zones displayed enhanced temporal and spatial variability. Climate change effects on temperature and aridity zones imply that the patterns of cropping systems, macro-ecosystems, and human land use modes are potentially undergoing migration and modification due to climate change.

1 Introduction

Significant global warming occurred in the twentieth century and especially in the most recent decades. Global mean surface air temperature increased with a rate of 0.07 °C per decade from 1906 to 2005 (IPCC 2007), and a more dramatic temperature increase occurred in the latter 50 years (0.13 °C per decade), while precipitation during this period was highly variable spatially and temporally (IPCC 2007), which also led to evident drying in some regions. In China, even greater changes in climate were observed, where the mean surface air temperature increased by over 0.2 °C per decade over the last 50 years and precipitation was extremely variable. Pronounced warming and uneven precipitation in the northeast, south, and northwest regions of China brought different responses of evapotranspiration (ET), runoff, and soil moisture in the three regions (Piao et al. 2010; Ding et al. 2007). Unbalanced temperature and precipitation variation resulted in spatial heterogeneity of warming and drying patterns and processes. These substantially affects traditional geographical regions, such as agricultural zones (Qiu and Lu 1980; Qiu 1983, 1986, 1992), climatic zones (Wu et al. 2010), and life zones (Chen et al. 2003), as climate factors are key components in geographical regionalization.

The eastern part of Inner Mongolia in China (Eastern Inner Mongolia) is located on the interface between the cold

temperate zone and the middle temperate zone and also on the interface of agricultural, forest, and grassland biomes (Zhou et al. 2007; Shao et al. 2006; Dianfa et al. 2000). Previous studies using mean temperature and precipitation data indicated that Eastern Inner Mongolia has experienced significant warming and drying (Zhang et al. 2011); the mean air temperature increased with an average rate of 0.3–0.4 °C per decade during 1955–2005 (Li et al. 2009), which was higher than that of the country as a whole (Ding et al. 2007). The warming and drying trends have been even more pronounced since the late 1970s (Lu et al. 2009), which substantially impacted the pattern of water and thermal conditions, as well as fragile regional ecosystems and environment.

Previous studies have used temperature and precipitation as the main indicators to examine climate change (Lu et al. 2009; Tao and Zhang 2011; Lobell and Burke 2008). However, accumulated thermal condition, which consists of an integral heat provision, is one of the most important indicators representing agricultural climate resources and has an important influence on cropping intensity, crop calendar, cropping systems, and crop distribution (Yan et al. 2011; Bartholomew and Williams 2005; Li et al. 2008; Dong et al. 2009), as plants need certain cumulative thermal conditions for growth and development. For example, The annual accumulated temperature above 10 °C (AAT10) has been used to define geographic temperature zones in China (Wu et al. 2010; Qiu 1986; Dong et al. 2009). The aridity index (AI), an indicator to assess regional drying by considering both rainfall and evapotranspiration (Wu et al. 2005; Shen et al. 2009), has been used as an important indicator to define aridity zones in geographical regionalization. Both AAT10 and AI have proved effective in illuminating the macropattern of thermal and water conditions at regional scale (Qiu 1992; Zheng et al. 2008). Thus, AAT10 and AI were used to explore warming and drying processes from climate change and their effects on temperature and aridity zones in this study.

Although traditional geographical regionalization can identify macroscale patterns for thermal and water conditions and is widely used for national development planning (Mccabe et al. 1990; Wang et al. 2004), most regionalizations are static and tend to be outdated due to recent changes in climatic patterns. Indicators for regionalization include both dynamic (e.g., climate factors) and static factors (e.g., terrain and soil), and the multiyear mean of the dynamic factor has been often adopted to get the average status of several years (Zheng et al. 2008). However, recent changes in climate have substantially altered the climate-related factors in geographical regionalization, which has further impacted the pattern of geographical zones, and few studies have documented the potential effects of climate change on traditional geographical zones (Wu et al. 2010).

The objective of this study is to investigate the warming and drying processes over the past 50 years in a typical agricultural-forest–grassland ecotone (Eastern Inner Mongolia), with particular foci on (1) the spatiotemporal pattern of warming and drying and (2) their effects on the shifting of temperature and aridity zones. The temperature and aridity zones were delineated according to AAT10 and AI indicators and the periodic change characteristics of warming and drying were examined by piecewise regression. The relationships of warming and drying processes were quantified via spatial correlation analysis of AAT10 and AI. The potential implications on ecosystems and land use change were then discussed with the aim to improve the regional adaptation ability to climate change.

2 Data and methods

2.1 Study area

Eastern Inner Mongolia is located in northeastern China between 115° 13′–126° 04′ E and 45 °24′–53° 23′ N, including five cities (Hulun Buir League, Xing'an League, Tongliao City, Chifeng City, and Xilin Gol League), with a total area of 66.58×10^4 km² (Fig. 1a). The topography in the region is hierarchical. The Da Hinggan Mountains, with elevations of 700–1,700 m, stretch from northeast to southwest and are a dividing line of terrain, climate, and agriculture (Zhou et al. 2007). The Inner Mongolia Plateau is located west of the mountains, while the expansive plains span across Northeast China on the east. Furthermore, humid and arid zones are located on the two sides of the mountains with an annual precipitation of approximately 500–800 mm occuring on the east of the mountains and 300–500 mm occuring on the west. The mountains also divide land use types into agriculture, pastoral farming, and forestry. For example, a large area of grassland is located in the western region of Eastern Inner Mongolia, farmland is mainly distributed in the low-humidity valleys in the east, and forest is the main land cover in the northern part of the Da Hinggan Mountains (Fig. 2b). Cool temperatures, limited water resources, and poor soil are the main restricting factors for agriculture in the study area.

Eastern Inner Mongolia has experienced substantial climate and land use change over the last 50 years (Liu et al. 2005; John et al. 2009; Lu et al. 2009), which has impacted the inherently vulnerable ecosystems. As a border region of geographical zones, this region is a typical area for exploring the warming and drying processes and their effects on temperature and aridity zones. The understanding about warming and drying and their effects on the ecosystems and land use will contribute to regional sustainable development.
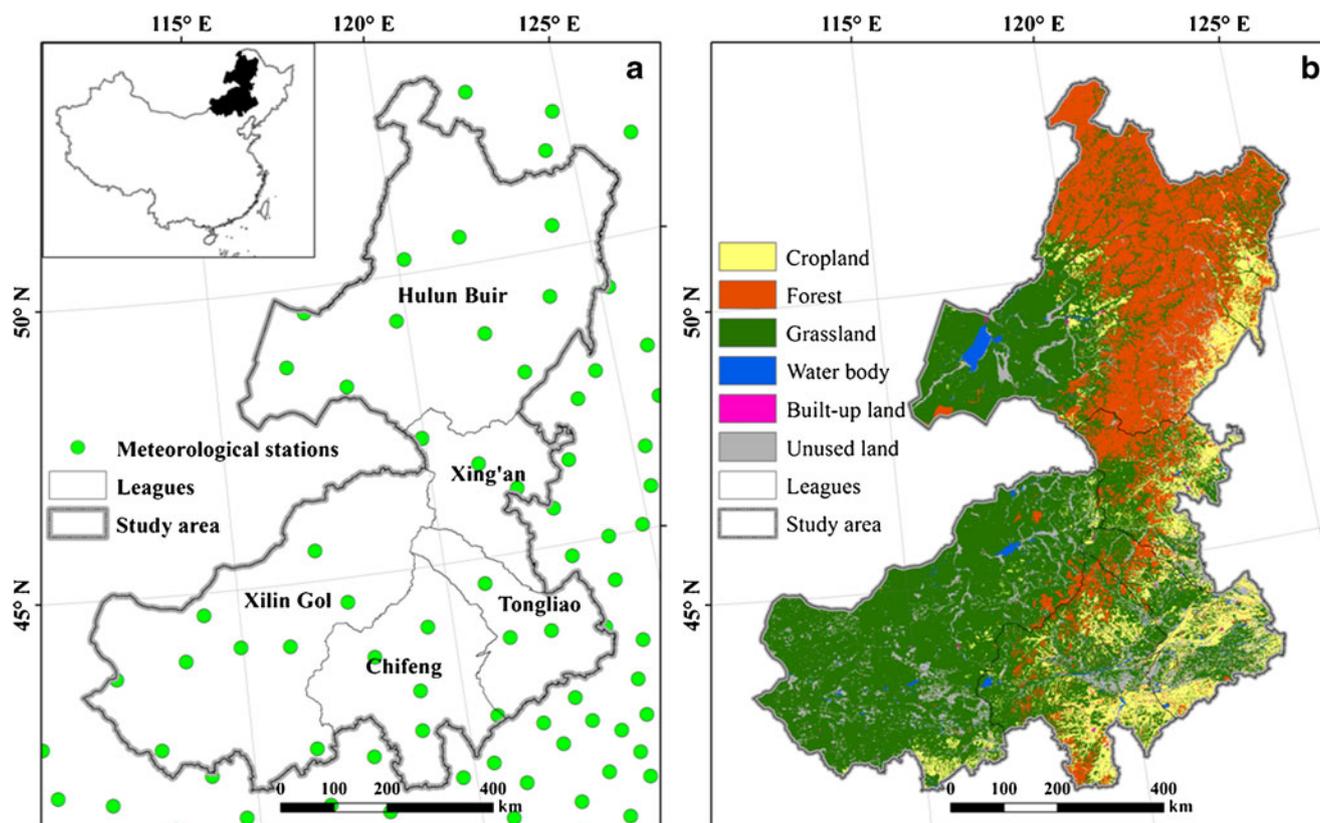
Fig. 1 **a** The location of study area in China, the distribution of the meteorological stations, and **b** the spatial distribution of main land cover types in 2000

2.2 Data acquirement and interpolation

We used observational meteorological data from weather stations in and nearby Eastern Inner Mongolia, including 29 stations inside the study area and other stations outside the study area (Fig. 2a). All available stations in Northeastern China were used in the data analysis, to guarantee the accuracy of spatial interpolation. The data was obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), served by National Meteorological Information Centre. A series of daily indicators, including mean temperature, minimum temperature, maximum temperature, precipitation, wind speed, sunshine hours, and relative humidity were used.

All climate data were spatially interpolated into a surface grid with a resolution of 1×1 km by using the method of thin-plate smoothing splines, through ANUSpline 4.2 software (Hutchinson 2001) which incorporates topography in the spatial interpolation. The 1×1 km digital elevation model (DEM) data, resampled from a Shuttle Radar Topography Mission DEM with a resolution of 90×90 m (Jarvis et al. 2008), was utilized in the interpolation process. This method has performed well in the interpolation of climatic data versus other methods such as inverse distance weighted and kriging (Jiang et al. 2010).

2.3 Warming assessment and the division of temperature zones

AAT10 is defined as the sum of daily mean temperatures above 10 °C in a continuous period of 1 year. If temperature values exceed 10 °C for five consecutive days, then the AAT10 is calculated from the first day of those five days and extends until the final day above 10 °C. AAT is calculated using the following formula:

$$\text{AAT10} = \sum_{i=1}^{n} \overline{T_i} \quad \left(\overline{T_i} > 10 \right) \tag{1}$$

where $\overline{T_i}$ is the mean air temperature on day i, $i = 1, 2, 3, \ldots, n$ and n is the total number of the days when daily mean temperature values are larger than 10 °C continuously; therefore, $T_i > 10$ °C.

AAT10 is a key criteria to divide different temperature zones in traditional physical geographical regionalization in China (Dong et al. 2009; Qiu 1983; Table 1). The temperature zones were divided into five zones, following the previous climatic regionalization of China, including the tropical zone, the subtropical zone, the warm temperate zone (WTZ), the middle temperate zone (MTZ), and the cold temperate zone (CTZ) with 8,000, 4,500, 3,400, and
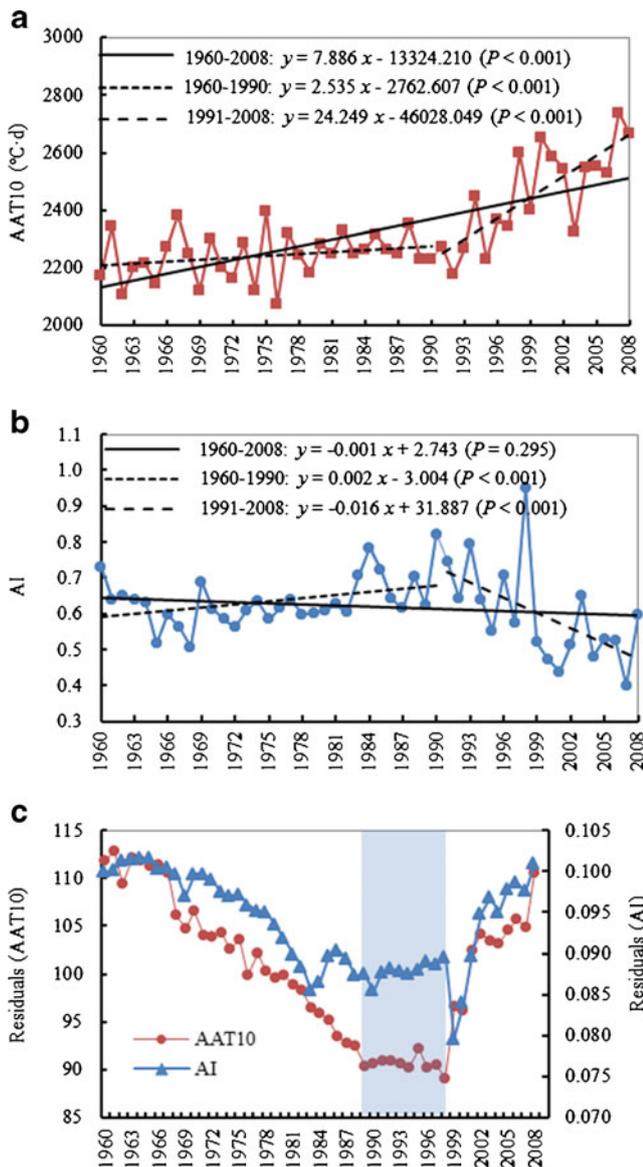
Fig. 2 Inter-annual variation of **a** AAT10 and **b** AI for the total region. The linear fitting lines for three periods are shown. The breakpoints of piecewise regression were defined by using **c** the residuals of annual AAT10s and AIs

1,600 °C·d as threshold values (Table 1). The different zones correspond with certain crops and cropping systems (Dong et al. 2009). The tropical and subtropical zones didn't exist in the study region.

2.4 Drying assessment and the division of aridity zones

The aridity index is a classic indicator to assess moisture conditions by considering both evapotranspiration and precipitation (Bannayan et al. 2010; Arora 2002; Onder et al. 2009) and is similar in principle to the moisture index of

C.W. Thornthwaite (Mccabe and Wolock 1992; Mccabe et al. 1990). The AI was calculated as follows,

$$I_m = \frac{p}{ET_0} \qquad (2)$$

where I_m is the AI, p is the precipitation, and ET_0 is the potential evapotranspiration.

Potential evapotranspiration is the most critical component of AI, and is affected by solar and terrestrial radiation, temperature, wind speed, vapor pressure, and other environmental factors. A variety of methods exist to calculate potential evapotranspiration (Wang et al. 2004; Wu et al. 2005); in this study, we applied the revised version of the Food and Agriculture Organization Penman–Monteith model (Allen et al. 1998). All the parameters in the potential evapotranspiration calculation were determined according to the previous studies presented by Wu et al. (2005) and Zhao et al. (2010).

As shown in Table 1, five aridity zones were separated according to AI, including the arid zone (AZ), semi-arid zone (SAZ), semi-arid-humid zone (SAHZ), sub-humid zone (SHZ), and humid zone (HZ), with AI values of 0.2, 0.5, 0.65, 1, and 1.45, respectively as thresholds referring to previous related studies (Wang et al. 2004; Shen et al. 2009).

2.5 Trends of warming and drying

As previous research has shown that climate change in this region has periodic characteristics (Lu et al. 2009), we applied a piecewise regression model that joins two straight linear lines at a breakpoint to examine warming and drying trends (Toms and Lesperance 2003),

$$y_{(x)} = \begin{cases} \beta_0 + \beta_1 x + e_i & (x \le \alpha) \\ \beta_0 + \beta_1 x_i + \beta_2(x - \alpha) + e_i & (x > \alpha) \end{cases} \qquad (3)$$

where $y_{(x)}$ is the AAT10 or AI value for the xth year, x is the corresponding year, α is the turning point (TP) year, and e_i is the residual random error. The slopes of the lines are β_1 and β_2 in preceding and following periods, which reflect the magnitudes of the warming and drying rates in two periods. If the slope of AAT10 is greater than 0, it means warming occurred. Likewise, if the slope of AI is less than 0, it means drying occurred. After verifying the TP year of the AAT10 and AI variation for the entire region, trends of warming or drying at pixel scale in preceding and following periods were estimated using the least square method separately.

To evaluate whether it is reasonable to apply the piecewise regression, a Student's t-test is used to test the statistical significance of piecewise regression. The residuals for AAT10, shown in Fig. 2c, demonstrate that the breakpoint

Table 1 Division criteria of temperature zones and aridity zones referring to exiting studies (Qiu 1983; Dong et al. 2009; Wang et al. 2004; Shen et al. 2009)

AAT10 (°C)	>8,000	4,500–8,000	3,400–4,500	1,600–3,400	<1,600
Temperature zones	Tropical zone	Subtropical zone	Warm temperate zone	Middle temperate zone	Cold temperate zone
Aridity index (unitless)	0.04–0.2	0.2–0.5	0.5–0.65	0.65–1	1-1.6
Aridity zones	Arid zone	Semi-arid zone	Semi-arid humid zone	Sub-humid zone	Humid zone

year is in the range of 1989–1995. In addition, the AI residuals yielded low values in the same range (1989–1995). Therefore, we used the year of 1990 as the mutual breakpoint for both warming and drying processes. The warming and drying processes were analyzed for the whole period (1960–2008) and two divided periods (1960–1990, 1991–2008). We partitioned drying trends into five levels according to the slope of drying (β_{AI}) with the equal internal classification method (Tables 2 and 3), including "extreme drying" ($\beta_{AI} < -0.015$), "severe drying" ($-0.015 < \beta_{AI} < -0.01$), "moderate drying" ($-0.01 < \beta_{AI} < -0.005$), "mild drying" ($-0.005 < \beta_{AI} < 0$), and "tending wetter" ($\beta_{AI} > 0$). Likewise, warming trends were divided into six levels according to the slope of warming (β_{AAT}) with the equal internal classification method as well, including: "tending cooler" ($\beta_{AAT} < 0$), "slight warming" ($0 < \beta_{AAT} < 5$), "mild warming" ($5 < \beta_{AAT} < 10$), "moderate warming" ($10 < \beta_{AAT} < 15$), "severe warming" ($15 < \beta_{AAT} < 20$), and "extreme warming" ($\beta_{AAT} > 20$).

3 Results

3.1 Temporal change at the regional level

The mean AAT10 of the whole region was calculated by averaging all the pixel values in the region. The warming process showed a significant linear increase ($n=49$, $p<0.001$) with an AAT10 increasing rate of 7.89 °C·d/year from 1960 to 2008 (Fig. 2a). The linear trend of AI for the entire study area during 1960–2008 was −0.0011/year (Fig. 2b), indicating that, generally, the study area tended to become drier during the 49-year period. However, the linear fit was not statistically significant ($n=49$, $p=0.295$) from 1960 to 2008 due to a change in the occurrence of slight wetting and pronounced drying events (Fig. 2b).

Both AAT10 and AI showed two discrete stages based on piecewise regression. Before 1990, the AAT10 increase was not statistically significant and the rate of increase was

Table 2 Tabulated area percentage statistics of different warming levels and their significance levels in three periods (1960–2008, 1960–1990, and 1991–2008)

Period	Significance	Cooler <0 (%)	Slight warming 0~5 (%)	Mild warming 5~10 (%)	Moderate warming 10~15 (%)	Severe warming 15~20 (%)	Extreme warming >20 (%)
1960–2008	$p>0.1$		1.6	0.0	0.0		
	$0.05<p<0.1$		0.3	0.2	0.0		
	$0.01<p<0.05$		1.6	0.6	0.0		
	$0.001<p<0.01$		2.1	2.0	0.0		
	<0.001		0.2	89.2	2.3		
	Area sum		5.6	92.1	2.3		
1960–1990	$p>0.1$	6.1	73.1	0.2			
	$0.05<p<0.1$	0.0	9.4	0.9			
	$0.01<p<0.05$	0.0	7.7	1.9			
	$0.001<p<0.01$	0.0	0.2	0.7			
	Area sum	6.1	90.3	3.6			
1991–2008	$p>0.1$				2.0	0.0	0.0
	$0.05<p<0.1$				2.8	0.5	0.0
	$0.01<p<0.05$				0.7	7.6	0.4
	$0.001<p<0.01$				0.0	4.6	30.6
	<0.001				0.0	0.0	50.7
	Area sum				5.5	12.7	81.8

Table 3 Tabulated area percentage statistics of different drying levels and their significance levels in three periods (1960–2008, 1960–1990, and 1991–2008)

Period		Significance	Extreme drying <−0.015 (%)	Severe drying −0.015~−0.01 (%)	Moderate drying −0.01~−0.005 (%)	Mild drying −0.005~0 (%)	Wetter >0 (%)
1960–2008	Drying	$p<0.001$			0.0	0.2	0.0
		$0.001<p<0.01$			0.1	0.7	0.0
		$0.01<p<0.05$			0.1	3.6	0.0
		$0.05<p<0.1$			0.0	5.7	0.0
		$p>0.1$			0.0	71.7	0.0
		$p>0.1$			0.0	0.0	17.5
	Wetting	$0.05<p<0.1$			0.0	0.0	0.3
		$0.01<p<0.05$			0.0	0.0	0.1
		Area sum			0.1	81.9	17.9
1960–1990	Drying	$p>0.1$				7.6	0.0
		$p>0.1$				0.0	70.7
	Wetting	$0.05<p<0.1$				0.0	16.3
		$0.01<p<0.05$				0.0	5.3
		Area sum				7.6	92.4
		$p<0.001$	6.4	0.2	0.0	0.0	0.0
		$0.001<p<0.01$	5.6	4.7	0.0	0.0	0.0
1991–2008	Drying	$0.01<p<0.05$	19.9	15.7	1.5	0.0	0.0
		$0.05<p<0.1$	6.3	6.3	2.3	0.0	0.0
		$p>0.1$	6.0	7.6	8.7	8.3	0.0
	Wetting	$p>0.1$	0.0	0.0	0.0	0.0	0.6
		Area sum	44.2	34.4	12.4	8.3	0.6

2.54 °C·d/year ($n=31$, $p<0.001$). However, after 1990, the AAT10 increase was significant with a dramatically larger rate of 23.76 °C·d/year ($n=18$, $p<0.001$; Fig. 2a). The whole region underwent a slight wetting process during 1960–1990, with an AI increase rate of 0.0018 ($n=31$, $p<0.001$); then AI showed a significant decrease from 1991 to 2008, although an outlier occurred in 1998 due to abnormal precipitation (Fig. 2b).

3.2 Spatial patterns of warming and drying trends in the region

3.2.1 Warming

The analysis in Section 3.1 showed a warming trend at the regional level from 1960 to 2008, and, in particular, since 1990. The spatial distribution of AAT10 trends with significance $p<0.1$ for three periods (1960–2008, 1960–1990, and 1991–2008) are shown in Fig. 3a–c. During the entire study period from 1960 to 2008, most parts of study area (92.1 %) experienced a warming trend (5–10 °C·d/year). In addition, the significance level was high ($p<0.001$) for 89.2 % of area (Table 2).

For the period spanning 1960–1990, warming was not as pronounced as that from the total 49 years. Most regions (90.3 % of the study area) yielded a slight warming trend

(Table 2); however, the warming was not statistically significant in most areas (Figs. 3b). From 1991 to 2008, significant warming occurred across the whole study area; 81.8 % of the study area yielded the extreme warming with a statistical significance of $p<0.01$ (Tables 2) with the most extreme values concentrated in the central region of study area including Xingan League, northern Xilin Gol League, and southern Hulun Buir City. In addition, 12.7 and 5.5 % of the region was at the level of the severe and moderate warming, respectively, and was primarily distributed in the north of Hulun Buir and parts of Chifeng and Tongliao Cities (Fig. 3c).

3.2.2 Drying

The spatial distributions of drying trends with significance $p<0.1$ are shown in Fig. 3d–f. From 1960 to 2008, most places were at the level of either mild drying or tending wetter (Fig. 3d). The mild drying level had an areal proportion of 81.9 %, of which 71.7 % area was not statistically significant ($p>0.1$), 4.5 % was significant at $p<0.05$, and 5.7 % was associated with low significance $0.05<p<0.1$ (Table 3).The tending wetter level was located in the southern parts of Xilin Gol League and limited areas of Hulun Buir and Chifeng Cities and was not significant ($p>0.1$; Fig. 3d).
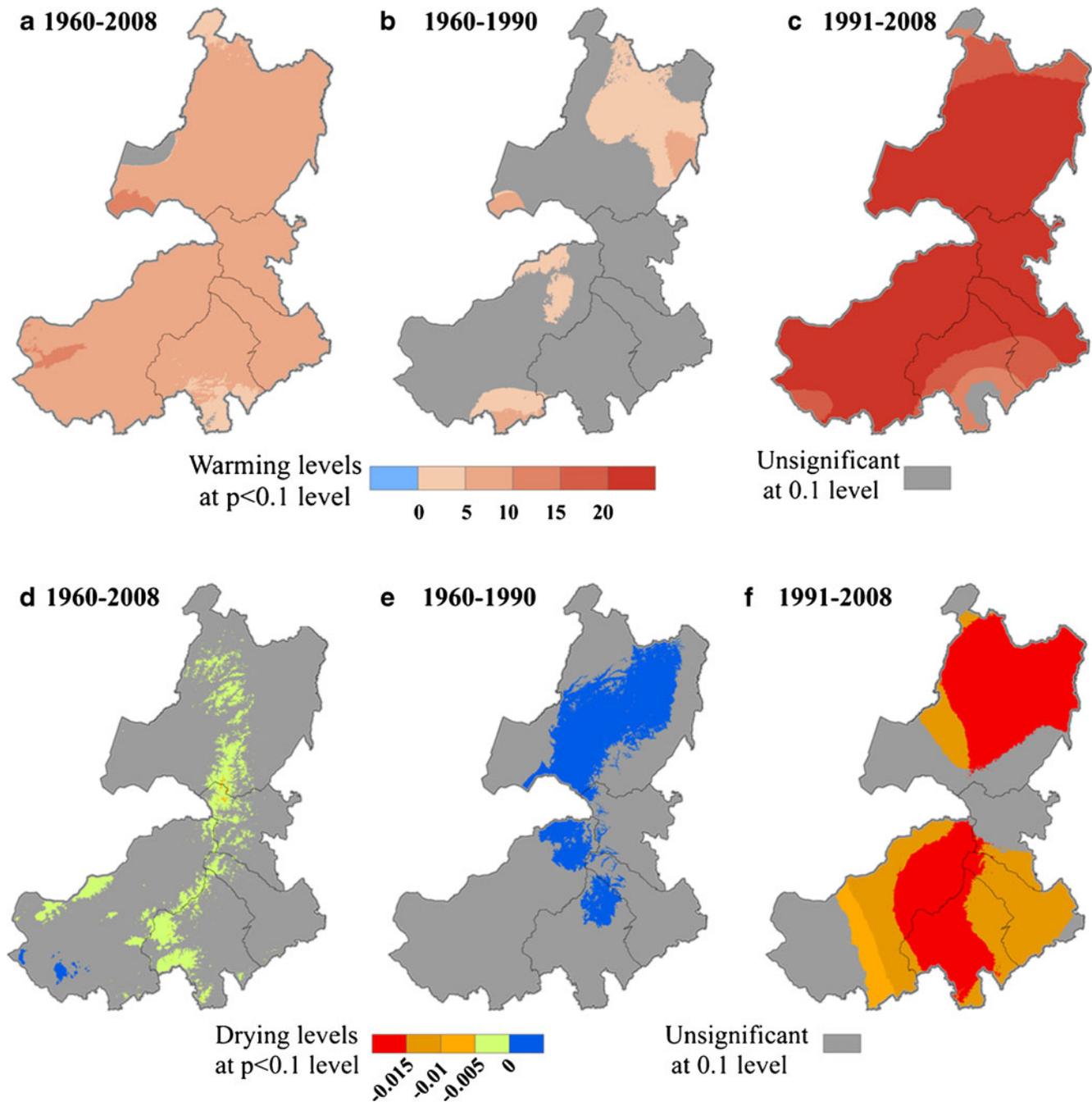
Fig. 3 Spatial distributions of different warming levels at the significance level $p<0.1$ in three periods: **a** 1960–2008, **b** 1960–1990, and **c** 1991–2008; and spatial distributions of different drying levels at the significance level $p<0.1$ in three periods: **d** 1960–2008, **e** 1960–1990, and **f** 1991–2008

During 1960–1990, the tending wetter and mild drying levels accounted for 92.4 and 7.6 % of the study area, respectively (Table 3). The area of tending wetter was large, but the significance level was low: only 21.6 % of the area has a significance of $p<0.1$ (Table 3) and was concentrated in the central part of Hulun Buir (Fig. 3e); while 70.7 % area was not statistically significant ($p>0.1$). From 1991 to 2008, 44.2 % of the area was at the level of extreme drying, of which 31.9 % was significant ($p<0.05$; Table 3) and was spatially distributed in the middle of the study area. Furthermore, 34.4 % of area was associated with the level of severe drying (20.6 % with $p<0.05$, and 6.3 % with $0.05<p<0.1$), while moderate drying and mild drying occurred in 12.4 and 8.3 % of the study area, respectively (Fig. 3f). Very little area displayed wetting trend.

3.3 Shiftings of temperature and aridity zones in response to climate change

3.3.1 Changes in temperature zones

The temperature zones were divided to track the effects from climate warming at decadal scales (Fig. 4a–e). A northward shift of temperature zones was evident. The proportion of CTZ decreased from 14.8 % in the 1960s, to 13.7 % in the 1970s, to 13.3 % in the 1980s, and to 11.1 % in the 1990s before reaching a minimum value of 5.5 % in the 2000s (Table 4). Conversely, there was no WTZ area in the 1960s, 1970s, and 1980s (0.02 %). The WTZ appeared in the eastern parts of Tongliao City in 1990s with an areal percentage of 2.3 %, and finally expanded to most parts of Tongliao City and a small part of Chifeng City with a total coverage of 10.3 % in the 2000s (Fig. 4a–e, Table 4), where abundant of cropland are located (Fig. 1b). The MTZ area changed little, staying approximately at 85 %. However, the spatial location shifted northward along with the movements of the CTZ and WTZ. A large area converted from the MTZ to the WTZ in the southern part of the study area, and from the CTZ to MTZ in northern parts. The boundary of the two zones shifted northward (Fig. 4). In theory, this could alter the cropping index from "one crop a year" to "three crops in 2 years." This deduction was based upon previous studies,

which have shown that the northern boundary of winter wheat growth has moved northward in Northeast China (Yun et al. 2007; Xiao et al. 2007; Dong et al. 2009).

3.3.2 Changes in aridity zones

The aridity zones did not show the same shifts as the temperature zones, but did yield large spatial and temporal variations. During the 1960s, the HZ was located in the northern part of Hulun Buir, covering 13.1 % of the study area. It then shifted northward in the 1970s, but expanded southward again in the 1980s, then slightly shrank to north again in the 1990s, before it moved into extremely northern parts of Hulun Buir with an areal proportion of only 2.2 % in the 2000s. Although the HZ area percentage was very small in the 1970s, the SHZ was large with a percentage of 32.9 %. If we consider HZ and SHZ together as "relative humid zones", then the areal percentage changed from 39.8 % in the 1960s and the 1970s, to 40.5 % in the 1980s, to 49.5 % in the 1990s and to 27.4 % in the 2000s when it shrank rapidly after 2000 (Table 4). Most regions of Xingan League were covered by the SHZ before 2000, which changed into the SAHZ and SAZ during the 2000s. The AZ region changed little from the 1960s to 2000s. However, the SAZ displayed dramatic variation, particularly with a rapid decrease from 31.5 % in the 1980s to 22.1 % in
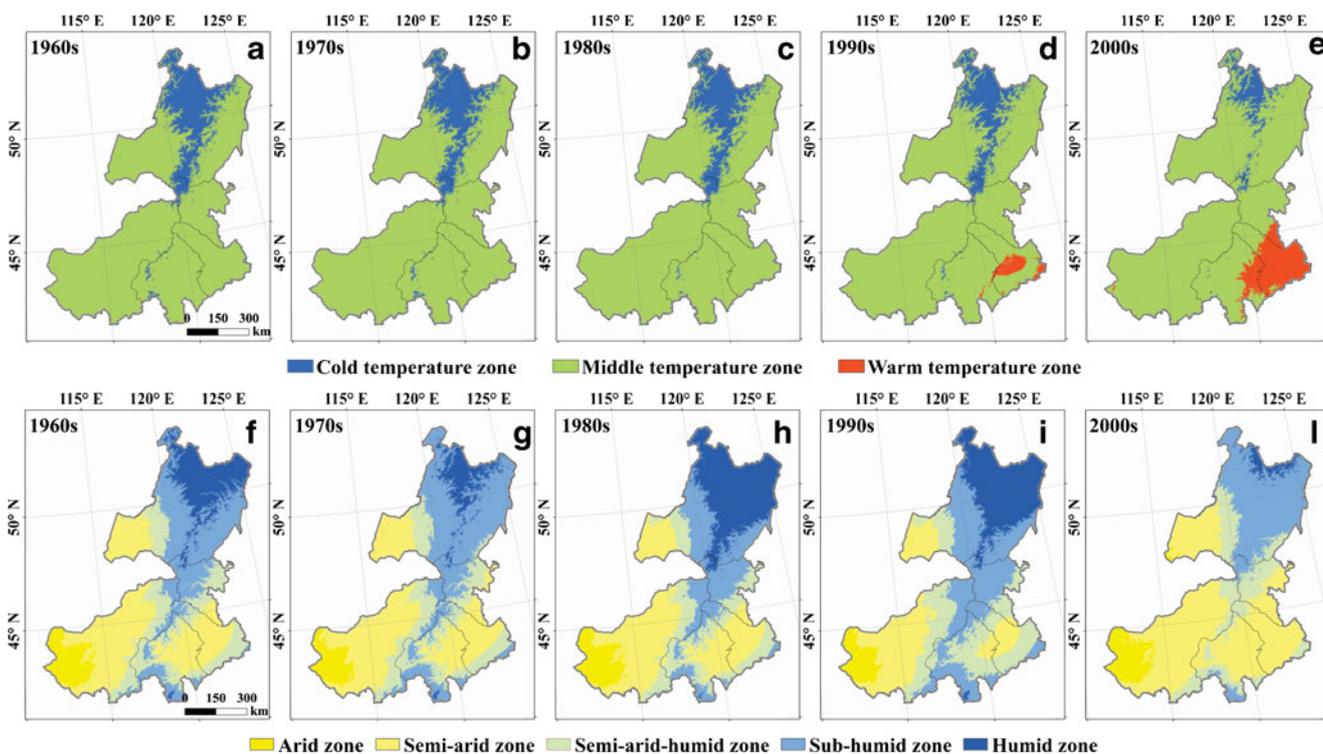
Fig. 4 The spatial patterns of temperature zones in **a** the 1960s, **b** the 1970s, **c** the 1980s, **d** the 1990s and **e** the 2000s; aridity zones in **f** the 1960s, **g** the 1970s, **h** the 1980s, **i** the 1990s, and **j** the 2000s

Table 4 The area percentages of temperature zones and aridity zones in five periods according to the decade mean of AI and AAT10: the 1960s (1960–1969), the 1970s (1970–1979), the 1980s (1980–1989), the 1990s (1990–1999), and the 2000s (2000–2008)

	Zones	1960s (%)	1970s (%)	1980s (%)	1990s (%)	2000s (%)
Temperature zones	CTZ	14.76	13.68	13.25	11.08	5.53
	MTZ	85.23	86.31	86.73	86.65	84.15
	WTZ	0.00	0.00	0.02	2.27	10.32
Aridity zones	AZ	6.47	4.92	6.48	4.76	6.70
	SAZ	33.15	34.01	31.45	22.14	48.28
	SAHZ	20.55	21.29	18.47	23.61	17.61
	SHZ	26.72	32.91	22.05	29.94	25.22
	HZ	13.12	6.86	21.56	19.55	2.19

the 1990s, and an increase into 48.3 % in the 2000s, which indicates SAZ underwent a rapid expansion in the 2000s.

4 Discussion

4.1 The relationship between warming and drying trends

Warming and drying trends showed similar temporal characteristics with the same breakpoint around 1990. As such, the warming and drying are perhaps related to some extent in the study area. Figure 5a shows the scatter plot of AAT10s and AIs at the regional level for the 49 years of study. The correlation between AAT10 and AI during 1960–2008 was −0.34, which is statistically significant ($p<0.05$, $n=49$). If the abnormal year of 1998 was excluded, the correlation coefficient would change to −0.54 with higher statistical significance ($p<0.0001$, $n=49$). Thus, warming and drying are significantly negatively correlated at the regional level.

However, is this relationship valid for all the pixels of the study area? Figure 5b shows the spatial pattern of significance levels for the correlations within each pixel. The variations of warming and drying in 1960–2008 were not entirely spatially correlated. Significant correlation ($p<0.05$) occurred in the middle of Hulun Buir League and central Xilin Gol League and parts of Chifeng City (Fig. 5b). Such spatial imbalance between warming and drying trends demonstrates the complexity of climate change effects (Ma 2005). The complicated relationship between warming and drying results from the temporal and spatial variations of precipitation to a large extent; furthermore, the increase in air temperature accelerates both evapotranspiration and plant water requirement.

4.2 Potential effects of warming and drying on ecosystems and land use

Climatic conditions determine the distribution of a species or biomes to a large extent (Stephenson 1990; Salazar and Nobre

Fig. 5 a The scatter plot of AAT10s and AIs for the total study region and **b** the spatial distribution of the significance of the correlation of AAT10s and AIs from 1960 to 2008

$$AI = 1.1129 - 0.0002 * AAT10$$
$$(n = 49, p = 0.0188)$$
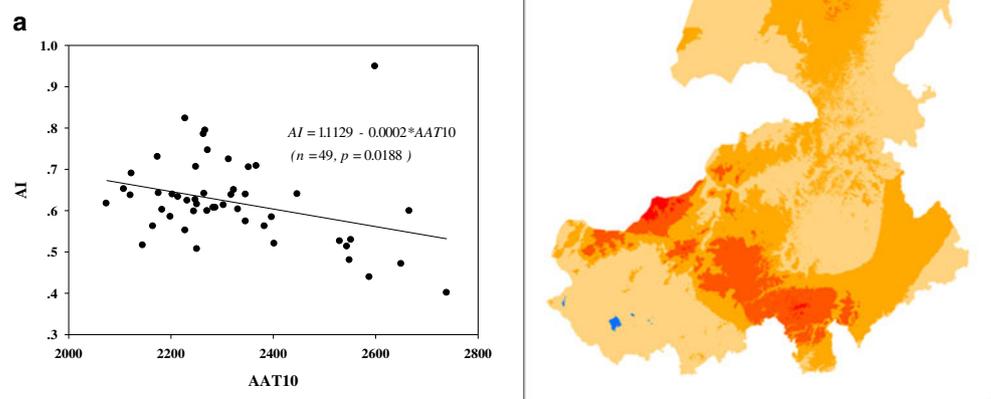
2010; Hanewinkel et al. 2010; Salazar et al. 2007). Thus, climate change can result in species' migration when it exceeds the tolerable climatic range of those species (Walther et al. 2005), and species survival chances can depend on their migration rates and ability to keep pace with climate change (Loarie et al. 2009). Climate change velocity may be faster than the migration speed of protected species. Rapid warming and drying have altered the spatial distribution of different biomes substantially in the study area. By simulating major terrestrial ecosystems with the Holdridge Life Zone Model, Zhang et al. (2011) demonstrated that climate warming and drying affects ecosystems in Inner Mongolia. Warming, especially an AAT10 increase, has possible impacts on cropping index and land reclamation (Dong et al. 2009). The temperature zone transition from 1,600–3,400 °C to 3,400–4,500 °C was obvious in Eastern Inner Mongolia (Fig. 5d and e) and could lead to an expansion in the boundary of winter wheat, as indicated by existing studies (Li et al. 2008; Yan et al. 2005). For example, Yun et al. (2007) showed that the growth boundary of winter wheat has moved northward by 10° in latitude. Spring wheat has been replaced gradually by winter wheat for more production in some places where climate became suitable for winter wheat.

The interaction between climate change and land use change had an important influence on ecological processes (Scientific Steering Committee of the Land-Use/Cover Change 2006). Many studies have explored the effects of land use and land cover change on climate change (Pielke 2005; Mahmood et al. 2006; Li et al. 2006) and it has been shown that land use change is an important impact factor in climate change because it alters surface albedo and the atmospheric concentration of carbon dioxide and methane (Pielke 2005). However, the effects of climate change on land use change need to be further explored (Pielke 2005; Mahmood et al. 2006). For this study, land use change occurred dramatically in the study area in past decades and climate warming could be an important factor or precondition for land reclamation and agricultural expansion (Dong et al. 2009; Gao and Liu 2011). The cropland in the Eastern Inner Mongolia underwent a continuous increase from 1990 to 2005 from 6.5×10^4 to 7.6×10^4 km^2 (Dong et al. 2011), which could be related to the significant warming from 1991 to 2008 (Fig. 3c); also, the pattern of the new land reclamation is consistent with the warming. However, the mechanism becomes more complicated due to anthropogenic influences. Additional factors could include growing population and food demand, the national policy such as "the Grain for Green project", and the implementation of ecological restoration projects.

4.3 Uncertainty of warming and drying trends

The effects of climate change on temperature and aridity zones were examined at a decadal scale. However, a decadal mean could ignore significant variations of moisture conditions within the decade. For example, although water conditions were very good in 1998 due to the abnormal precipitation, drying tended to deteriorate over the whole 1990s (Fig. 2b).

Future warming and drying trends also have uncertainties. A simulation based on future climate scenario data from the regional climate model of PRECIS showed that temperature zones in China would shift northward in the twenty first century (Wu et al. 2010). On the one hand, warming could be advantageous to enable cropping in some regions where it used to be unsuitable. On the other hand, future warming could aggravate drought in some regions, increase crop pests and diseases, and lead to additional requirements of pesticides and fertilizers. For example, Kim and Byun (2009) applied daily precipitation data from 15 coupled climate models simulated under the SRES A1B scenario in Asia in late the twenty first century and found that parts of the Eastern Asia could undergo slight increases in drying frequency and intensity due to more uncertain precipitation. Therefore, in the future, a durative warming and unstable drying will probably enhance in Eastern Inner Mongolia. As such, it is urgent for us to improve the capability to respond and adapt to a dryer and warmer environment.

5 Conclusion

As a region composed of different climate and biome types, Eastern Inner Mongolia is a hotspot for climate change studies. We used AAT10 and AI to assess the warming and drying change processes from 1960 to 2008, and explored climate change impacts on temperature and aridity zones. Our study demonstrated that stronger warming and drying trends occurred after 1990 than the preceding 31 years (1960–1990). Significant warming led to the shifting of temperature zones and that potentially impacted the cropping system and the patterns of biomes. In addition, a drying trend was significant in most regions since 1991 as well, which may have made the fragile environment more vulnerable. Overall, this study demonstrates how climate change affects traditional temperature and aridity zones. The movement of temperature and aridity zones could trigger ecosystem migration and land use change. However, the evidence and velocity of ecosystem migration and adaption in response to the shifting of temperature and aridity zones require more research. Furthermore, the relationships between warming, drying, and agricultural land use (e.g., cropping structure and index) should be further explored in the future. A systematic investigation on the processes, drivers, and effects of drying and warming is critical for adaption to climate change in future.

References

Allen RG, Pereira LS, Raes D, Smith M, Food and Agriculture Organization of the United Nations (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO irrigation and drainage paper, vol 56. Food and Agriculture Organization of the United Nations, Rome

Arora VK (2002) The use of the aridity index to assess climate change effect on annual runoff. J Hydrol 265(1–4):164–177

Bannayan M, Sanjani S, Alizadeh A, Lotfabadi SS, Mohamadian A (2010) Association between climate indices, aridity index, and rainfed crop yield in northeast of Iran. Field Crop Res 118 (2):105–114

Bartholomew PW, Williams RD (2005) Cool-season grass development response to accumulated temperature under a range of temperature regimes. Crop Sci 45(2):529–534

Chen XW, Zhang XS, Li BL (2003) The possible response of life zones in China under global climate change. Glob Planet Chang 38(3–4):327–337. doi:10.1016/S0921-8181(03)00115-2

Dianfa Z, Nianfeng L, Jie T (2000) Formation mechanismof eco-geo-environmental hazards in the agro-pastoral interlocking zone of northern China. Environ Geol 39(12):1385–1390

Ding Y, Ren G, Zhao Z, Xu Y, Luo Y, Li Q, Zhang J (2007) Detection, causes and projection of climate change over China: an overview of recent progress. Adv Atmos Sci 24(06):954–971

Dong JW, Liu JY, Tao FL, Xu XL, Wang JB (2009) Spatio-temporal changes in annual accumulated temperature in China and the effects on cropping systems, 1980s to 2000. Clim Res 40(1):37–48

Dong JW, Liu JY, Yan HM, Tao FL, Kuang WH (2011) Spatio-temporal pattern and rationality of land reclamation and cropland abandonment in mid-eastern Inner Mongolia of China in 1990–2005. Environ Monit Assess 179(1–4):137–153. doi:10.1007/s10661-010-1724-9

Gao J, Liu YS (2011) Climate warming and land use change in Heilongjiang Province, Northeast China. Appl Geogr 31(2):476–482. doi:10.1016/j.apgeog.2010.11.005

Hanewinkel M, Hummel S, Cullmann DA (2010) Modelling and economic evaluation of forest biome shifts under climate change in Southwest Germany. Forest Ecol Manage 259(4):710–719. doi:10.1016/j.foreco.2009.08.021

Hutchinson MF (2001) Anusplin Version 4.2 User Guide

IPCC (2007) Summary for policymakers of climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge

Jarvis A, Reuter HI, Nelson A, Guevara E (2008) Hole-filled SRTM for the globe. Version 4. Available from the CGIAR-CSI SRTM 90 m database (http://srtm.csi.cgiar.org)

Jiang X, Liu X, Huang F, Jiang H, Cao W, Zhu Y (2010) Comparison of spatial interpolation methods for daily meteorological elements. Chin J Appl Ecol 21(3):624–630

John R, Chen J, Lu N, Wilske B (2009) Land cover/land use change in semi-arid Inner Mongolia: 1992–2004. Environ Res Lett 4 (4):045010. doi:10.1088/1748-9326/4/4/045010

Kim DW, Byun HR (2009) Future pattern of Asian drought under global warming scenario. Theor Appl Climatol 98(1–2):137–150. doi:10.1007/s00704-008-0100-y

Li Q, Ding Y, Dong W (2006) A numerical simulation on impact of historical land-use changes on regional climate in China since 1700. Acta Meteorol Sin 3:257–270

Li J, Gao P, Chen Y, Chen H, Yang T, Huang J, Jin Z, Peng D (2008) Relationships between farming system and effective accumulated temperature in East China. Chin J Ecol 27(03):361–368

Li X, Guo R, Yang L, Hou Q (2009) Changes of precipitation and temperature and its impacts on agriculture in recent 50 years in Eastern Inner Mongolia. Scientia grographica sinica 29(05):755–759

Liu JY, Liu ML, Tian HQ, Zhuang DF, Zhang ZX, Zhang W, Tang XM, Deng XZ (2005) Spatial and temporal patterns of China's cropland during 1990–2000: an analysis based on Landsat TM data. Remote Sens Environ 98(4):442–456

Loarie SR, Duffy PB, Hamilton H, Asner GP, Field CB, Ackerly DD (2009) The velocity of climate change. Nat 462(7276):1052–1055, http://www.nature.com/nature/journal/v462/n7276/suppinfo/nature08649_S1.html

Lobell DB, Burke MB (2008) Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environ Res Lett 3(3):034007

Lu N, Wilske B, Ni J, John R, Chen J (2009) Climate change in Inner Mongolia from 1955 to 2005—trends at regional, biome and local scales. Environ Res Lett 4(4):045006. doi:10.1088/1748-9326/4/4/045006

Ma ZG (2005) Dry/wet variation and its relationship with regional warming in arid-regions of northern China. Chin J Geophys-Chin Ed 48(5):1011–1018

Mahmood R, Pielke RA, Hubbard KG (2006) Land use/land cover change and its impacts on climate. Glob Planet Chang 54(1–2):VII

Mccabe GJ, Wolock DM (1992) Effects of climatic change and climatic variability on the thornthwaite moisture index in the Delaware River Basin. Clim Chang 20(2):143–153

Mccabe GJ, Wolock DM, Hay LE, Ayers MA (1990) Effects of climatic-change on the Thornthwaite moisture index. Water Resour Bull 26(4):633–643

Onder D, Aydin M, Berberoglu S, Onder S, Yano T (2009) The use of aridity index to assess implications of climatic change for land cover in Turkey. Turk J Agric For 33(3):305–314

Piao SL, Ciais P, Huang Y, Shen ZH, Peng SS, Li JS, Zhou LP, Liu HY, Ma YC, Ding YH, Friedlingstein P, Liu CZ, Tan K, Yu YQ, Zhang TY, Fang JY (2010) The impacts of climate change on water resources and agriculture in China. Nat 467(7311):43–51. doi:10.1038/Nature09364

Pielke RA (2005) Land use and climate change. Science 310 (5754):1625–1626. doi:10.1126/science.1120529

Qiu B (1983) Further study on the regionalization of agroclimate of China. Acta Geographica Sinica 2:154–162

Qiu B (1986) A new discussion on the regionalization of agroclimate in China. Acta Geographica Sinica 3:202–209

Qiu B (1992) Some notes on the map of agricultural physical regionalization in China and its tables. J Henan Univ (Nat Sci) 4:69–73

Qiu B, Lu Q (1980) A tentative regionalization of agroclimate of China. Acta Geographica Sinica 2:116–125

Salazar LF, Nobre CA (2010) Climate change and thresholds of biome shifts in Amazonia. Geophys Res Lett 37. doi:10.1029/2010gl043538

Salazar LF, Nobre CA, Oyama MD (2007) Climate change consequences on the biome distribution in tropical South America. Geophys Res Lett 34(9). doi:10.1029/2007gl029695

Scientific Steering Committee of the Land-Use/Cover Change P (2006) Conclusion. In: Land-Use and Land-Cover Change. pp. 173–176

Shao XQ, Kun W, Dong SK, Huang XX, Kang MY (2006) Regionalisation of suitable herbages for grassland reconstruction in agro-pastoral transition zone of northern China. New Zeal J Agr Res 49(1):73–84

Shen S, Zhang F, Sheng Q (2009) Spatio-temporal changes of wetness index in China from 1975 to 2004. Trans CSAE 25(01):11–15

Stephenson NL (1990) Climatic control of vegetation distribution: the role of the water balance. Am Nat 135(5):649–670

Tao FL, Zhang Z (2011) Impacts of climate change as a function of global mean temperature: maize productivity and water use in China. Clim Chang 105(3–4):409–432. doi:10.1007/s10584-010-9883-9

Toms JD, Lesperance ML (2003) Piecewise regression: a tool for identifying ecological thresholds. Ecology 84(8):2034–2041

Walther G-R, Beißner S, Burga CA (2005) Trends in the upward shift of alpine plants. J Veg Sci 16(5):541–548. doi:10.1111/j.1654-1103.2005.tb02394.x

Wang L, Xie X, Li Y, Tang D (2004) Changes of humid index and borderline of wet and dry climate zone in northern China over the past 40 years. Geogr Res 23(01):45–54

Wu SH, Yin YH, Zheng D, Yang QY (2005) Aridity/humidity status of land surface in China during the last three decades. Sci China Ser D-Earth Sci 48(9):1510–1518

Wu SH, Zheng D, Yin YH, Lin ED, Xu YL (2010) Northward-shift of temperature zones in China's eco-geographical study under future climate scenario. J Geogr Sci 20(5):643–651. doi:10.1007/s11442-010-0801-x

Xiao G, Zhang Q, Wang J (2007) Impact of global climate change on agro-ecosystem: a review. Chin J Appl Ecol 18(08):1877–1885

Yan H, Liu J, Cao M (2005) Remotely sensed multiple cropping index variations in China during 1981–2000. Acta Geographica Sinica 60(4):559–566

Yan M, Liu X, Zhang W, Li X, Liu S (2011) Spatio-temporal changes of ≥10 °C accumulated temperature in northeastern China since 1961. Chin Geogr Sci 21(1):17–26. doi:10.1007/s11769-011-0438-4

Yun Y, Fang X, Wang L, Qing T (2007) Adapted regulation of crop grown borderline to climate warming in China. Crops 03:20–23

Zhang G, Kang Y, Han G, Sakurai K (2011) Effect of climate change over the past half century on the distribution, extent and NPP of ecosystems of Inner Mongolia. Glob Chang Biol 17(1):377–389. doi:10.1111/j.1365-2486.2010.02237.x

Zhao Z, Liu J, Shao Q (2010) Spatial diversity of humidification and its impact on ecosystem venerability in china during the last 30 years. J Nat Res 25(12):2091–2100

Zheng D, Ou Y, Zhou CH (2008) Understanding of and thinking over geographical regionalization methodology. Acta Geographica Sinica 63(06):563–573

Zhou ZY, Sun OJ, Huang JH, Li LH, Liu P, Han XG (2007) Soil carbon and nitrogen stores and storage potential as affected by land-use in an agro-pastoral ecotone of northern China. Biogeochemistry 82(2):127–138